U.S. AIR FORCE

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RESEARCH MEMORANDUM

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RAND RESEARCH MEMORANDUM

PRESSURE RESPONSE WITHIN AN ENCLOSURE SUBJECT TO A BLAST WAVE

W. R. Elswick

RM-2660 March 1, 1961

in brief

Technical problems associated with hardened base facilities have been under continual investigation at RAND. A part of this work concerns the design of shelter structures to withstand the blast or pressure-rise effects of a nuclear explosion. This research memorandum treats one aspect of the problem.

A generalized mathematical model is presented of the rise of pressure with time within an enclosure as a function of enclosed volume, leakage-opening area, static overpressure, and nuclear weapon yield. The results are shown graphically. Their applicability to the design of protected enclosures is illustrated by two examples of personnel shelters: a small home shelter, and a considerably larger arrangement housing up to a hundred people.

This information should be useful in evaluating protective-construction design, particularly as it is affected by the incorporation of heating and ventilation subsystems.

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SUBJECT TO A BLAST WAVE

W. R. Elswick

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Assigned to ____________________

This research is sponsored by the United States Air Force under contract No. AF 49(638)-700 monitored by the Directorate of Development Planning, Deputy Chief of Staff, Development, Hq USAF.

The RAND Corporation

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SUMMARY

A blast shelter or other similar enclosure normally has numerous openings leading to the outside for ingress and egress, ventilation, and utility lines. Thus, there is a possibility of air leakage because of an ineffective or defective door seal, or an inoperative or open valve in the ventilation system.

Any leakage to the inside of high-pressure air resulting from a nuclear blast wave would tend to raise the pressure within the shelter. The magnitude of the rise depends on the shock strength, the time duration of outside pressure, the sizes of the leakage area, and the shelter volume.

For certain conditions, such as large internal shelter volume and small opening areas, such items as door seals and blast valves in the ventilation system may not be necessary. Under these conditions, a nuclear blast wave could not cause an appreciable pressure rise within the enclosure without physical destruction of some part of the structure.

A somewhat idealized model of a blast shelter has been analyzed for a large range of the applicable variables. The pressure-time history and the peak value of the internal pressure have been determined. The results of the analysis are presented in generalized form by means of a series of curves. In addition, two examples are presented which are representative of personnel blast shelters: first, a typical home shelter, and second, a shelter that might serve 50 to 100 people.

CONTENTS

SYMBOLS

A	effective orifice area or leakage area
B	constant
C	velocity of sound
D	constant
E	internal energy
g	gravitational constant
H	enthalpy, γ E
J	mechanical equivalent of heat
K	constant $= \gamma \sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$
P	absolute pressure
q	dynamic pressure
R	perfect gas constant
^{o}R	absolute air temperature in degrees Rankine
T	absolute temperature
t	time
t_o	time duration of positive phase of overpressure
V	shelter volume
W	weight of air
$\dot{W}$	weight flow rate
x	pressure ratio P_1/P_{2i}
x_o	pressure ratio P_{1i}/P_{2i}
y	pressure ratio P_2/P_{2i}
α	non-dimensional time t/t_o

β	constant in exponent
γ	ratio of specific heats = 1.4 for air
Δ	increment
ΔP_o	initial overpressure = $x_o - 1$
δ	constant in exponent
θ	sonic fill time V_2/AC_{1i}
ν	velocity
ρ	weight density
ϕ ()	function of ()

Subscripts

1	outside conditions
2	inside conditions
i	initial conditions
0	peak initial conditions
m	maximum value

I. INTRODUCTION

In the design of blast protective shelters or other enclosures, it is important that attention be given to door seals and ventilating openings. One reason is that the structural loading of an enclosure may be a function of the pressure rise resulting from leakage, as in the case of open hatches on a ship's hold.

An enclosure, when subjected to an exterior blast wave of finite duration, will leak from any opening. The pressure within will rise to some peak value and then decay as the flow through the opening reverses. Door seals and check valves in ventilating systems may be necessary to limit the inside pressure to a tolerable level; correspondingly, an open hatch allowing pressure equalization may protect the deck or hull of a ship from failure.

The purpose of this study is to analyze the pressure-time history within an enclosure as a function of enclosed volume, leakage opening area, static overpressure, and nuclear weapon yield. The peak pressure within the shelter for any specific set of conditions may then be determined. This information should be useful in engineering design as well as in the analysis of blast resistance.

II. ASSUMPTIONS

The enclosed volume or shelter is a single compartment having a volume, V_2, and an opening or orifice of area, A, leading to the outside. Further, the area, A, is small compared to the volume; that is, the area may be measured in fractions of a square foot, while the volume may be described by hundreds of cubic feet.

The shelter volume opening system is critically damped; that is, the cavity does not resonate as a result of an external pressure stimulus. Viscous losses from opening and furnishings, other losses, and the limiting effect of the normal shock wave choking the opening and regulating the flow during the period when most of the mass flow occurs tend to inhibit oscillatory pressure fluctuations.*

The initial absolute pressure, P_{2i}, within the volume or enclosure is ambient atmospheric pressure (corresponding to 14.7 psi at sea level) prior to the arrival of the air shock wave. Upon arrival of the air shock the exterior portion of the opening experiences a sharp pressure rise. In this analysis the peak exterior absolute pressure, P_{1i}, is assumed to be the sum of the ambient pressure, P_{2i}, and the peak static overpressure, Δp, at the shock front. This may or may not be the proper estimate of the external pressure, depending on the geometry of the shock front and the exterior surface of the enclosure containing the opening. Thus in any calculation it may be necessary to modify the value of the overpressure, ΔP. As an example, consider the case of a door jamb leakage where the door is flush with the exterior of the enclosure which is parallel to the plane of the arriving air shock wave; that is, the shock strikes head-on

*Despite these damping effects, the criterion of resonance should be considered in shelter design.

with the opening. In this case the peak forcing pressure, P_{1i}, would be the sum of the preshock ambient pressure P_{2i}, the peak static overpressure ΔP, the diffraction pressure, and the peak dynamic pressure.(1-3) (Diffraction effects are of primary importance in cases of very high overpressures of about 100 atmospheres. The effect is usually of minor importance at low pressures of a few atmospheres, at least as far as leakage is concerned.) On the other hand, if the opening were on the downstream side of the structure the peak forcing pressure would be the sum of P_{2i} and ΔP minus a constant times the peak dynamic pressure q_{1i}. The value of the constant(4) depends on the exterior shape of the body (shelter) and the particle Mach number, and can vary from a maximum value of about 1.4 at low subsonic speeds to a value as small as 0.1 at Mach 5. At zero angle of incidence, surface normal to the plane of the shock wave, the constant becomes zero. Illustrative calculations in this memorandum will be on this basis. This condition can correspond to an opening through the flat horizontal top of an enclosure. The outside pressure variation with time is described by the relationship*

$$P_1 = P_{2i} + (P_{1i} - P_{2i}) \quad (1 - \frac{t}{t_o}) \quad \left[B\ e^{-\beta t/t_o} + D\ e^{-\delta t/t_o} \right] \qquad (1)$$

where the peak static overpressure $\Delta P = P_{1i} - P_{2i}$ and B, β, D, and Δ depend on the peak static overpressure. The time t_o, the duration of the positive pressure pulse, is a function of both peak pressure and weapon yield. Equation (1) can be rewritten in non-dimensional form as

$$\frac{P_1}{P_{2i}} = 1 + \left(\frac{P_{1i}}{P_{2i}} - 1 \right) \left(1 - \frac{t}{t_o} \right) \left[B\ e^{-\beta\, t/t_o} + D\ e^{-\delta\, t/t_o} \right] \qquad (2)$$

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*See the appendix.

The internal or shelter pressure, P_2, is assumed to be equal to the static pressure of the air flowing from the nozzle. That is, there is no recovery of the dynamic pressure in the air stream from the opening.

Air acts as an ideal diatomic gas in the overpressure range of interest (zero to perhaps 20 atmospheres).

The system is adiabatic. It is assumed that no energy is lost to the walls as the air is forced through the opening. In any real system there would, of course, be heat loss, especially as the effective length-to-diameter ratio of the opening increases. This assumption results in the prediction of slightly higher internal pressures than would actually be experienced.

The area of the opening is assumed to be the minimum section area in any conduit, seal, or other opening. However, in any real case there are losses such as the diffraction effects at the entrance, expansions and contractions within the channel, viscous effects at the walls, inertia or vena contracta effects at the minimum section, and exit effects. These effects all tend to restrict the flow; therefore, the effective area of any actual opening would, in general, be somewhat smaller than the minimum geometric area. This assumption also results in the prediction of internal pressures somewhat higher than in any real case.

The system is choked (flow velocity equal to Mach 1) at the minimum section of the opening as long as the pressure ratio remains critical ($\frac{P_2}{P_1} \leq 0.528$ for air).

III. ANALYSIS

The velocities and pressures involved can be described by an energy balance across the nozzle. For an ideal gas under adiabatic conditions and on a unit weight basis, the sum of the enthalpies and kinetic energies should be equal:

$$J \gamma E_1 + \frac{v_1^2}{2g} = J \gamma E_2 + \frac{v_2^2}{2g} \qquad (3)$$

However, the initial velocity v_1 is very low and may be neglected. Solving for the nozzle exit velocity v_2 we have

$$v_2^2 = 2gJ \gamma (E_1 - E_2) \qquad (4)$$

The weight-flow rate through the nozzle may be written as

$$\dot{W} = \rho_2 A v_2 = \rho_2 A \sqrt{2g J \gamma (E_1 - E_2)} \qquad (5)$$

The unit internal energy of a perfect gas can be expressed in terms of pressure and density as

$$E = \frac{P}{J\rho(\gamma-1)} \qquad (6)$$

The weight-flow rate (Eq. (5)) may then be rewritten as

$$\dot{W} = \rho_2 A \sqrt{2g \frac{\gamma}{\gamma-1} \left(\frac{P_1}{\rho_1} - \frac{P_2}{\rho_2}\right)} \qquad (7)$$

With the assumptions of adiabatic flow, no molecular changes, and reversible flow, $\frac{P_2}{P_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma}$, we can describe the weight-flow rate in terms of the inlet conditions and the pressure ratio across the nozzle, P_2/P_1.

Thus Eq. (7) becomes

$$\dot{W} = \left\{ A \quad 2g \frac{\gamma}{\gamma-1} \quad P_1 \rho_1 \left[\left(\frac{P_2}{P_1} \right)^{2/\gamma} - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma+1}{\gamma}} \right] \right\}^{1/2} \tag{8}$$

The flow rate is thus described as a function of the initial state of the shocked gas exterior to the shelter, the orifice area, and the pressure ratio across the orifice.

It should be noted that the weight-flow rate $\dot{W}$ as described by Eq. (8) passes through a maximum when plotted as a function of the pressure ratio P_2/P_1. The pressure ratio at which this maximum occurs is a function of the ratio of the specific heats of the gas. The maximum for any two of the three equation-of-state variables held constant can be determined by setting $d\,\dot{W}/d\,P_2$, derived from Eq. (8), equal to zero and solving for the nozzle pressure ratio:

$$\left(\frac{P_2}{P_1} \right)_{max} = \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}} \tag{9}$$

For normal air ($\gamma = 1.4$) the value of the pressure ratio at the maximum flow rate is very close to 0.528.

Recalling the energy balance from Eq. (4), the definition of internal energy (Eq. (6)), and the adiabatic relationship between density and pressure, we have by mutual substitution an expression for velocity in terms of the nozzle state variable and the pressure ratio:

$$v_2^{\,2} = 2g \frac{\gamma}{\gamma-1} \frac{P_2}{\rho_2} \left[\left(\frac{P_2}{P_1} \right)^{\frac{1-\gamma}{\gamma}} - 1 \right] \tag{10}$$

We may now solve for the velocity of maximum flow by substitution of $\left(\frac{P_2}{P_1}\right)_{max}$ from Eq. (9) in Eq. (10):

$$v_{2m}^{\ 2} = 2g \frac{\gamma}{\gamma-1} \frac{P_1}{\rho_1} = g\gamma \frac{P_2}{\rho_2} = C_2^{\ 2} \tag{11}$$

Thus, the flow velocity at this critical condition is equal to the local velocity of sound at the nozzle exit, C_2.

The nozzle would then limit the flow rate $\dot{W}$ (for any specific set of inflow state conditions P_1 and ρ_2) to the constant choked or sonic flow as long as the ratio of pressure within the shelter to the outside pressure is less than 0.528. The critical flow rate during choke flow would be represented by

$$\dot{W}_c = A\,\rho_2\,v_{2m} = A\rho_2\sqrt{2g \frac{\gamma}{\gamma+1} \frac{P_1}{\rho_1}} = A\sqrt{g\gamma\,P_1\rho_1 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{12}$$

For pressure ratios P_2/P_1 greater than 0.528 the flow velocity would be less than sonic and would be described by Eq. (8). The solid portion of the curve of Fig 1 is descriptive of the instantaneous flow rate corresponding to any value of the outside conditions and any pressure ratio across the nozzle. The flow rate variable $\dot{W}_c$ is that value of air flow described by any two of the three state variables P_1, ρ_1, and T, and values of P_2 and P_1 such that the ratio P_2/P_1 is 0.528. The ordinate of Fig. 1 is thus expressed in multiples of the critical flow rate. The expression for the curve between 0.528 and 1 is

$$\phi\left(\frac{P_2}{P_1}\right) = \frac{\dot{W}}{\dot{W}_c} = \frac{\left[\left(\frac{P_2}{P_1}\right)^{2/\gamma} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]^{1/2}}{\left[\frac{\gamma-1}{2}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{1/2}} \tag{13}$$

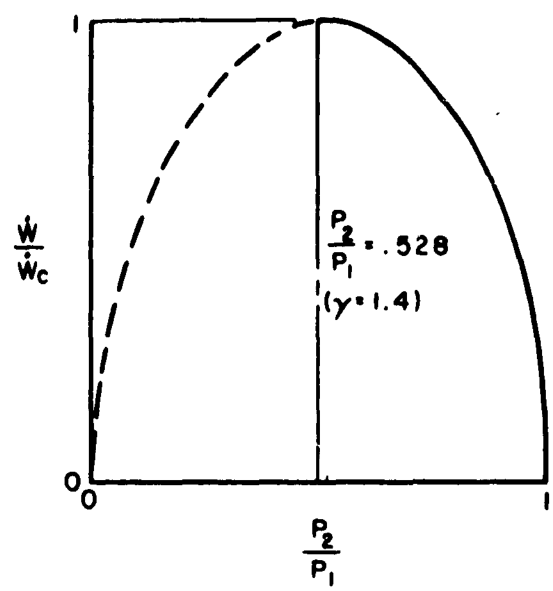


Fig. 1 — Nozzle flow rate in terms of critical or choked flow

The pressure and temperature within the enclosure may be related by the perfect gas law

$$P_2 V_2 = \left(W_{21} + W_{12}\right) R T_2 \tag{14}$$

A heat balance relates temperature and flow

$$\left(W_{12} + W_{21}\right) C_v T_2 = W_{12} \gamma C_v T_{1i} + W_{21} C_v T_{21} \tag{15}$$

Eliminating T_2 between the above equations and solving for P_2 we have

$$P_2 = \frac{\gamma R W_{12} T_{1i}}{V_2} + P_{21} \tag{16}$$

The variation of the internal pressure with time may be determined by differentiating with respect to time

$$\dot{P}_2 = \frac{\gamma R T_{1i}}{V_2} \dot{W}_{12} = \frac{\gamma R T_{1i}}{V_2} \dot{W}_c \left(\frac{\dot{W}_{12}}{\dot{W}_c}\right) \tag{17}$$

The ratio $\dot{W}/\dot{W}_c$ and the expression for $\dot{W}_c$ have been determined previously. Substituting the expression for $\dot{W}_c$ from Eq. (12) in Eq. (17) we have

$$\dot{P}_2 = \frac{\gamma R T_{1i}}{V_2} A \left[P_1 \rho_1 g \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{1/2} \frac{\dot{W}_{12}}{\dot{W}_c} \tag{18}$$

But recalling that $\rho_1 = \dfrac{P_1}{RT_1}$, $\dfrac{T_1}{T_{1i}} = \left(\dfrac{P_1}{P_{1i}}\right)^{\frac{\gamma+1}{\gamma}}$ and that $C_{1i} = \sqrt{\gamma g RT_{1i}}$

(19)

$$\dot{P}_2 = \frac{\gamma A C_{1i} P_1}{V_2} \left(\frac{P_{1i}}{P_{21}} \frac{P_{21}}{P_1}\right)^{\frac{\gamma-1}{2\gamma}} \sqrt{\frac{2}{\gamma+1}^{\frac{\gamma+1}{\gamma-1}}} \frac{\dot{W}_{12}}{W_c} \tag{20}$$

or in non-dimensional form

$$\frac{dy}{d\alpha} = \frac{t_o}{\Theta} \, x^{\frac{\gamma+1}{2\gamma}} \, x_o^{\frac{\gamma-1}{2\gamma}} \, K \, \phi \left(\frac{y}{x}\right) \tag{21}$$

or for air, $\gamma = 1.4$

$$\frac{dy}{d\alpha} = \frac{t_o}{\Theta} \, x^{6/7} \, x_o^{1/7} \, 0.81 \, \phi \left(\frac{y}{x}\right)$$

where

$$y = \frac{P_2}{P_{21}} , \; x = \frac{P_1}{P_{21}} , \; x_o = \frac{P_{11}}{P_{21}} , \; \alpha = \frac{t}{t_o} , \; K = \gamma \sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} , \; \phi \left(\frac{y}{x}\right) = \frac{\dot{W}_{12}}{\dot{W}_c}$$

and $\Theta = V_2/A \, C_{11}$.

The quantity x is defined by means of Eq. (2) in dimensionless form

$$x = 1 + (x_o - 1) \, (1 - \alpha) \left[B \, e^{-\beta\alpha} + D \, e^{-\delta\alpha}\right] \tag{22}$$

We now wish to determine y as a function of α (shelter pressure as a function of time) for various values of x_o (static overpressure), for a range of the variable t_o/Θ (the ratio of the positive duration of the overpressure to the minimum possible fill time), and for values of the constants B, β, D, and δ, which are functions of the peak static overpressure.

The solution is valid only for flow into the shelter or until the pressure inside rises to its maximum, which is also equal to the instantaneous outside pressure P_1; i.e., $P_1 = P_2$. This condition also corresponds to both $\dot{W}$ and $\dot{P}_2$ equal to zero. Therefore, as shown by Eq. (21)

and Fig. 1, for this condition

$$\left(\frac{P_2}{P_1}\right)_{max} = \left(\frac{y}{x}\right)_{max} = 1 \tag{23}$$

and

$$y_{max} = x = 1 + (x_o - 1)\,(1 - \alpha)\,\left[B\,e^{-\beta\alpha} + D\,e^{-\delta\alpha}\right] \tag{24}$$

Thus we know that the loci of maxima in y for any discrete value of x must fall along the curve of Eq. (24). This is illustrated in Fig. 2.

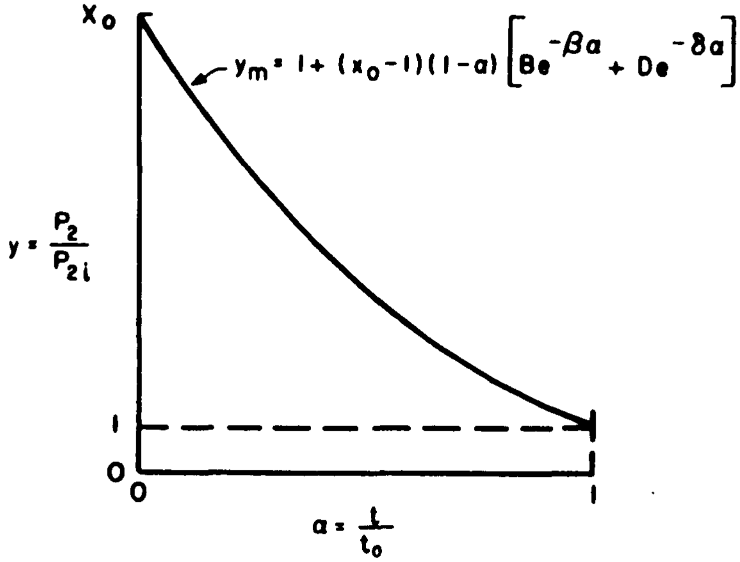


Fig. 2 — Loci of solutions for maximum shelter pressure as a function of time

Of course no solution for the maximum exists at any time greater than t_o, the duration of the positive phase of the overpressure.

This does not provide an explicit solution; in fact there is an infinite number of solutions for the maxima along the curve of Fig. 2. The problem of integrating Eq. (21) remains.

IV. RESULTS

Equation 21 has been solved numerically for several values of the static overpressure: 1, 3, 5, and 10 atmospheres. The results are presented in the curves of Figs. 3 to 6. The calculations of internal pressure as a function of time have been carried only to the condition of maximum internal pressure. In general, the pressure decay times will be greater than the rise times.

Figure 7 is a summary of the generalized solution for the maximum pressure rise to be expected within the shelter.

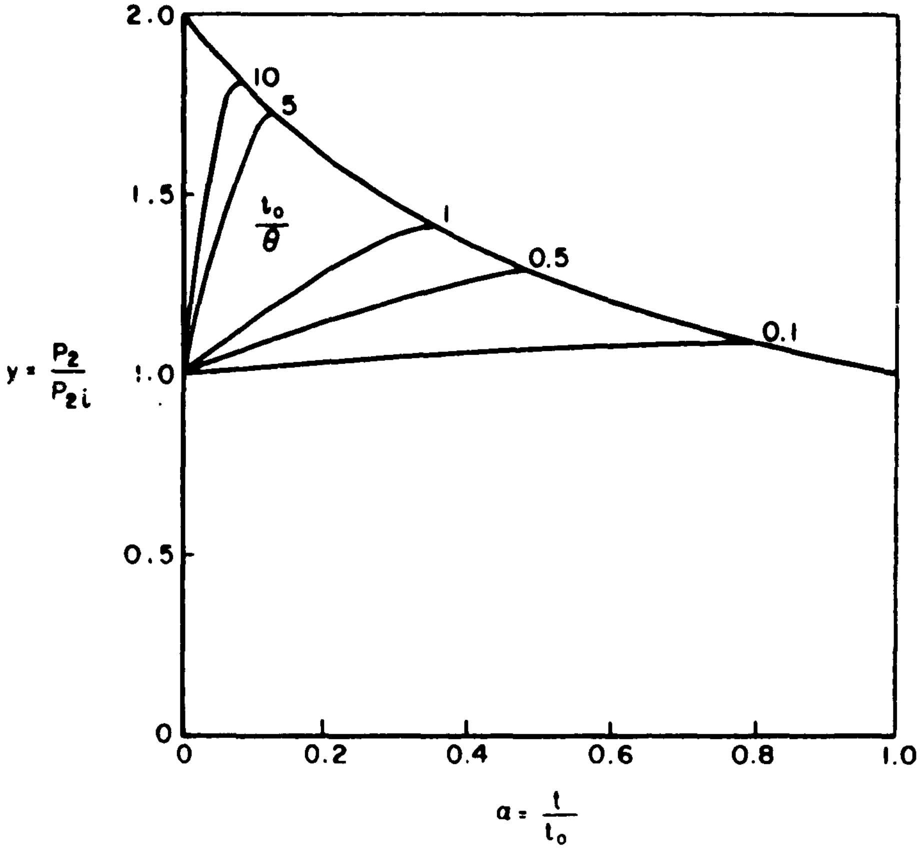


Fig. 3 — Pressure-time history within an enclosure
$X_0 = 2$, $\Delta P = 1$ atmosphere

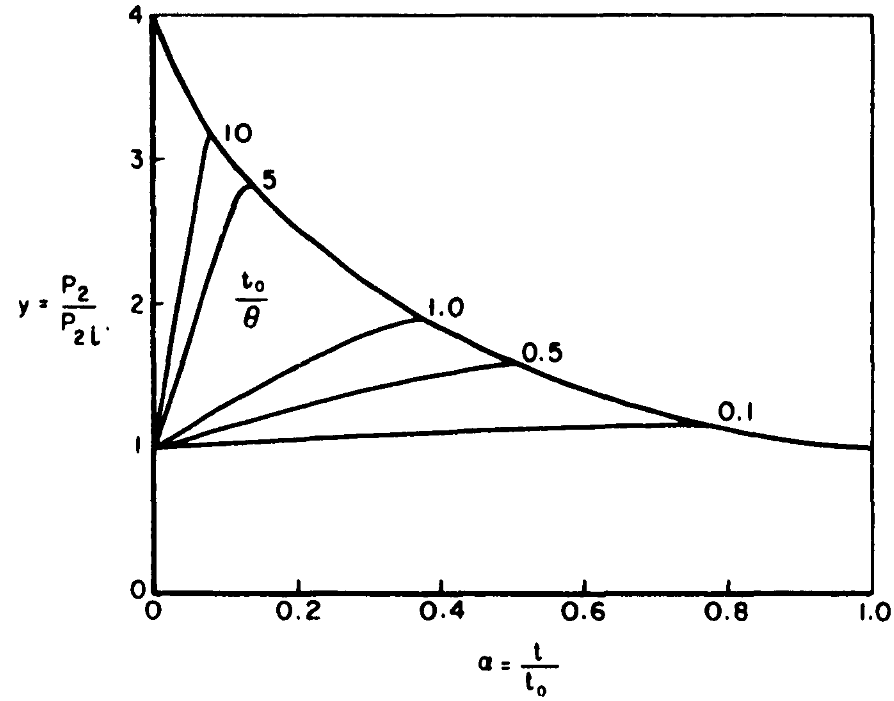


Fig. 4 — Pressure-time history within an enclosure
$X_0 = 4$, $\Delta P = 3$ atmospheres

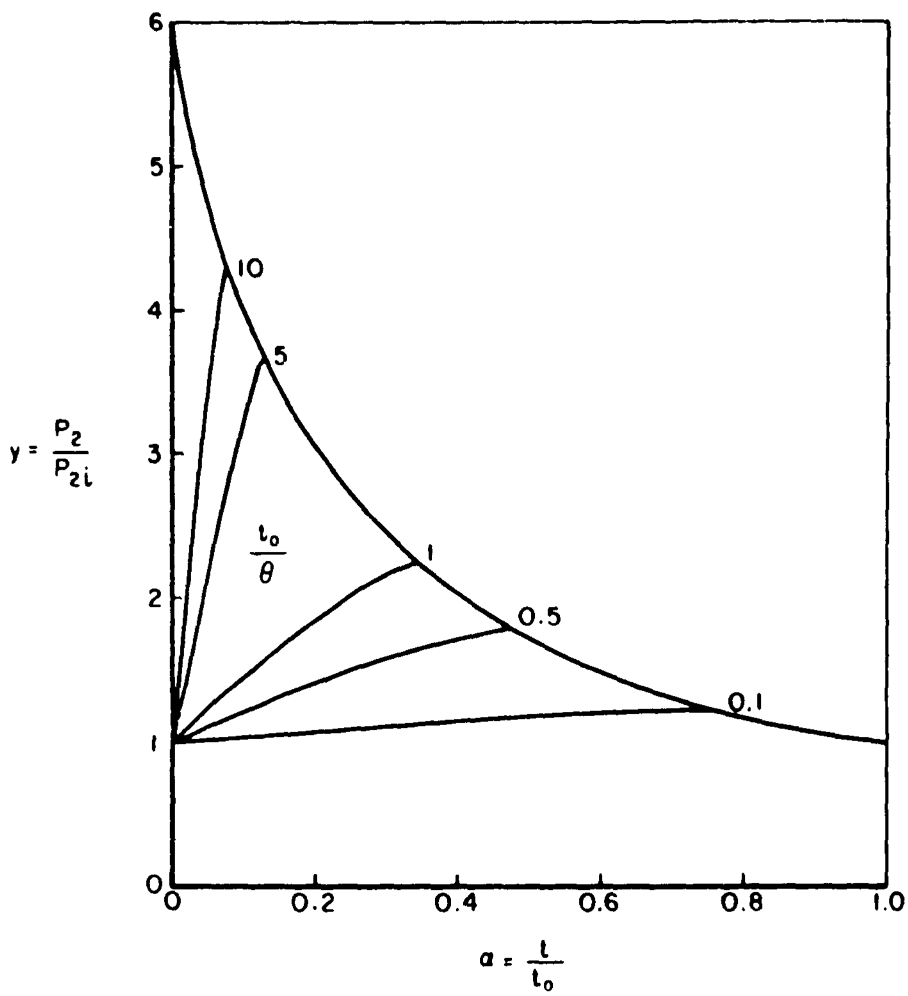


Fig. 5— Pressure-time history within an enclosure
$X_0 = 6$, $\Delta P = 5$ atmospheres

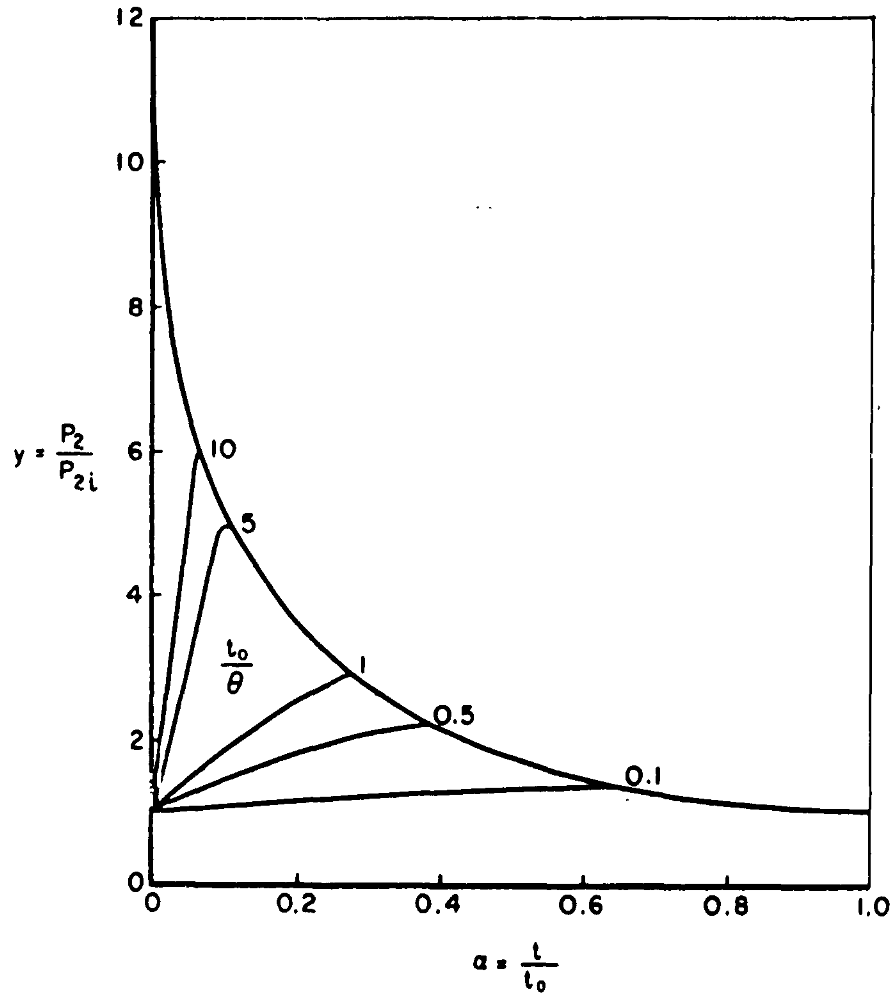


Fig. 6 — Pressure-time history within an enclosure
$X_0 = 11$, $\Delta P = 10$ atmospheres

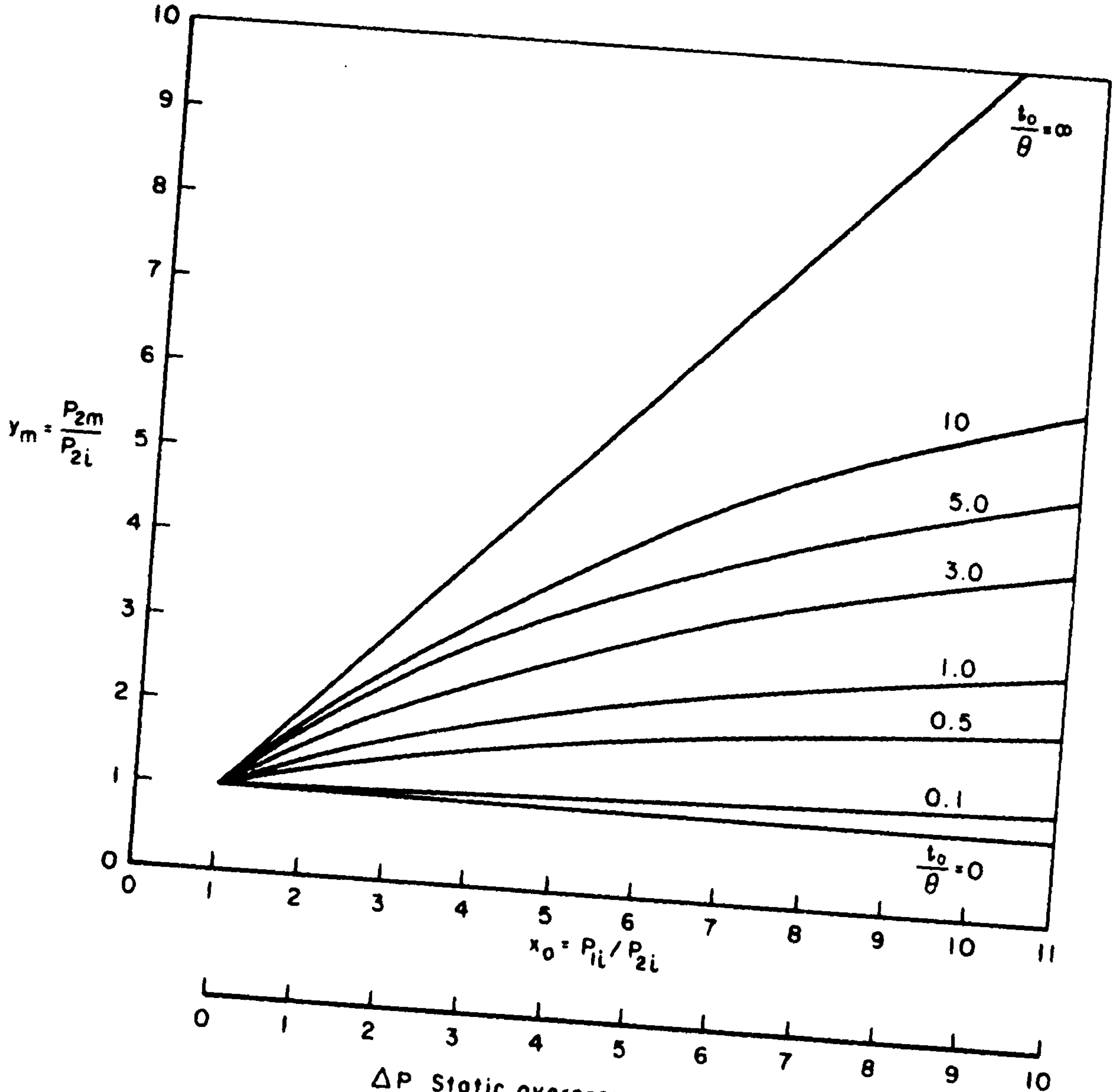


Fig. 7 — Solution for maximum pressure within an enclosure

V. NUMERICAL EXAMPLES

Example 1

As an example, let us consider a shelter, representative of a small home blast-and-fallout shelter, with the following significant properties:

Volume	$V_2 = 500\ \text{ft}^3$
Effective leakage area (3-in. inlet and 3-in. exhaust openings)	$A = 0.1\ \text{ft}^2$
Weapon yield	3-MT surface burst
Peak static overpressure	$\Delta P = 3$ atmospheres

Since the initial pressure ratio, $\frac{P_{21}}{P_{11}} = \frac{1}{4}$, is supercritical (less than 0.53), at the onset of the shock front we are interested in the temperature and the sonic velocity. The peak temperature associated with the shock front may be read from Fig. 9 (p. 29). The value for $\Delta P = 3$ atmospheres is 830°R. The initial choked velocity through the orifice is then

$$C_{11} = 1120 \sqrt{\frac{T_{11}}{520}}$$

$$= 1120 \sqrt{\frac{820}{520}} = 1415\ \text{ft/sec}$$

where the assumed preshock ambient temperature and sonic velocity are 520°R and 1120 ft/sec, respectively.

The sonic fill time θ then becomes

$$\theta = \frac{V_2}{AC_{11}} = \frac{500}{0.1\ (1415)} = 3.53\ \text{sec}$$

Brode's values of the positive duration time of the static overpressure

pulse are presented in Fig. 8 (p. 27). The values are descriptive of a sea-level 1-KT nuclear explosion which has been airburst. The positive duration of the airburst at an overpressure of 3 atmospheres is seen to be 0.093 sec. Assuming perfect reflection for a surface burst of a 3-MT weapon, the duration is

$$t_o = .093\ (2)^{1/3}\ (3000)^{1/3} = 1.73 \text{ sec (3 MT)}$$

Thus the time parameter becomes

$$\frac{t_o}{c} = \frac{1.73}{3.53} = 0.49$$

The solution for the maximum internal pressure may be read from Fig. 7. Entering with the static overpressure, 3 atmospheres, to a value of the time parameter, 0.49, one reads a value of peak pressure ratio

$$\frac{P_{2m}}{P_{21}} = 1.6$$

Thus the peak pressure rise within the shelter is 0.6 atmosphere or about 9 psi. Actually the pressure rise would probably be somewhat less.

Example 2

If the shelter were larger, say 5000 ft^3, had the same leakage area, 0.1 ft^2, and were exposed to an overpressure of 10 atmospheres from a 10-MT surface-burst nuclear weapon we would have:

$$V_2 = 5000 \text{ ft}^3$$

$$A = 0.1 \text{ ft}^2$$

$$W = 10 \text{ MT}$$

$$\Delta P = 10 \text{ atmospheres}$$

The peak static shock temperature would then be about $1050^{\circ}R$ and the shock velocity would be

$$C_{1i} = 1120 \sqrt{\frac{1050}{520}} = 1590 \text{ ft/sec}$$

The sonic fill-time becomes

$$\theta = \frac{5000}{0.1\ (1590)} = 31.2 \text{ sec}$$

The positive duration time, from Fig. 9, would be 0.08 sec for a 1-KT airburst weapon. The duration time for the surface-burst 10-MT weapon would be

$$t_o = 0.08\ (2)^{1/3}\ (10{,}000)^{1/3} = 2.2 \text{ sec}$$

The time parameter would be

$$\frac{t_o}{\theta} = \frac{2.2}{31} = .071$$

The maximum pressure ratio within the shelter would be (from Fig. 7)

$$\frac{P_{2m}}{P_{21}} = 1.25$$

The peak pressure within the shelter would be about 3.7 psi. As one would suspect, the sonic-choke principle of valving becomes most effective for large shelters having long sonic fill times as described by small values of the time parameter.

There are some complications evident in the second example. In a

ventilating system having a short pipe between the exterior and the interior of the shelter, hot luminous gas may pour from the opening. This possibility can, of course, be obviated by thoughtful design of the system. A good description of the environment at a close-in distance corresponding to high static overpressure from a nuclear weapon may be obtained from Refs. 1-3.

Appendix

PROPERTIES AT AND FOLLOWING THE SHOCK FRONT

STATIC OVERPRESSURE

The variation of static overpressure with time depends on the distance from the explosion center, hence the peak static overpressure. The overpressure profiles as well as the peak instantaneous pressure have been described by Brode[1,2] by means of a dichotomy of exponentials representing two decay rates

$$P_1 = P_{2i} + \left(P_{1i} - P_{2i}\right)\left(1 - \frac{t}{t_o}\right)\left[B\,e^{-\beta t/t_o} + D\,e^{-\delta t/t_o}\right]$$

where

$$B = \frac{2.28\left(8 + \Delta P_{1i}\right)}{27.66 + \Delta P_{1i} + 1.2\,\Delta P_{1i}^2 + .007\,P_{1i}^3} + 0.23$$

$$D = 1 - B$$

$$\beta = \sqrt{\frac{\Delta P_{1i}}{1 + .1\,\Delta P_{1i}}} + \frac{1.5\,\Delta P_{1i}^{\;2}}{1500 + \Delta P_{1i}^{3/2}}$$

$$\delta = 9.0 + 1.4\,\Delta P_s$$

and for 1 KT

$$t_o = \frac{0.1\,\Delta P_{1i}^2}{70 - 2\,\Delta P_{1i} + \Delta P_{1i}^2} + \frac{1}{20}\ln\frac{13}{\Delta P_{1i}}$$

(For $\Delta P_{1i} > 13$ omit the natural logarithm term.)

For weapon yields Y other than 1 KT

$$t_o = t_{o\text{-}1KT}\, Y^{1/3} \qquad \text{(Y in kilotons)}$$

Values of B, β, D, δ, and t_o are presented in Fig. 8.

DYNAMIC PRESSURE

Although values of the dynamic pressure have not been used in the calculations presented in this memorandum, Brode's values are presented for the sake of completeness. It is, of course, desirable to include the effect of dynamic pressure in the forcing pressure signal P_1 when the geometry and the consequent pressure recovery demand it.

Expressions similar to those representing static pressure have been used to represent the variation of dynamic pressure with time, although the dynamic pressure decays much more rapidly and goes through zero in a shorter period of time, t_x.

$$\Delta q_1 = \Delta q_{1i} \left(1 - \frac{t}{t_x}\right) \left[E\, e^{-\epsilon t/t_x} + Z\, e^{-\delta t/t_x}\right]$$

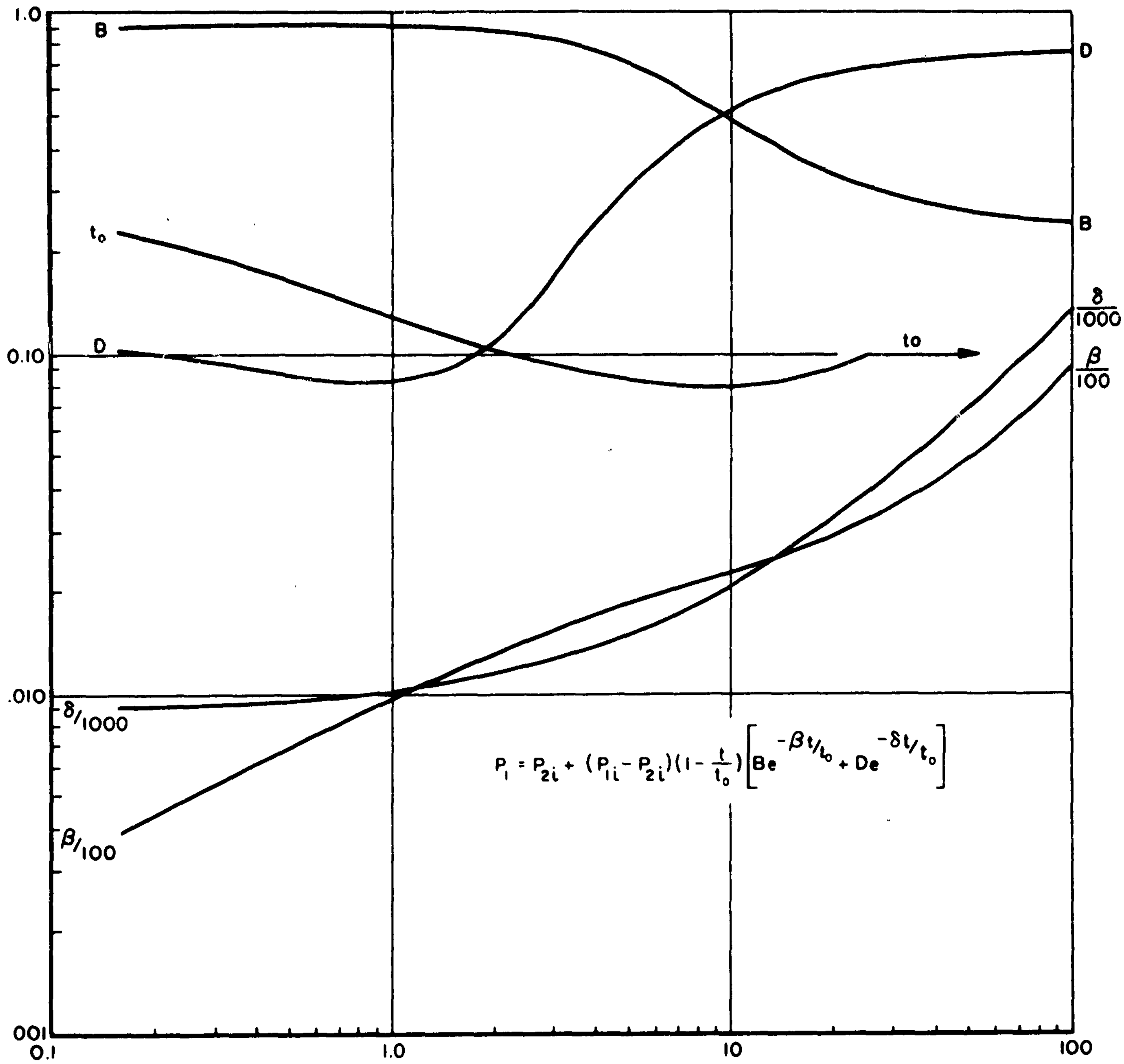
where

$$t_x = .0421 \ln \frac{85}{\Delta P_{1i}} \qquad (\text{for } \Delta P_{1i} < 33)$$

$$= .04 \qquad (\text{for } \Delta P_{1i} \geq 33)$$

$$E = \frac{10{,}000\, \Delta P_{1i}^{-1/4}}{10{,}000 + \Delta P_{1i}^2} \qquad (\text{for } \Delta P_{1i} > 1)$$

$$Z = 1 - E$$



Peak overpressure $\Delta P = P_{1i} - P_{2i}$ (atmospheres)

Fig. 8 — Values of parameters describing peak pressure vs time from a scaled 1-KT sea-level nuclear detonation

$$\epsilon = 0.25 + 3.6\sqrt{\Delta P_{11}}$$

$$\delta = 7 + 8\sqrt{\Delta P_{11}} + \frac{2\,\Delta P_{11}^2}{240 + \Delta P_{11}}$$

AIR TEMPERATURE

The velocity through the orifice during the period of choked flow is determined by the local sonic velocity, hence by the local temperature. The functional relationship for the sonic velocity is

$$C_{11} = 1120\sqrt{\frac{T_{11}}{520}} \qquad \text{ft/sec}$$

where T_{11} is measured in $^{\circ}$R and assuming a 60°F or 520°R day.

In regions of low overpressure, $\Delta P_{11} < 4$ atmospheres, the peak temperature occurs at the shock front and may be estimated from the adiabatic relationship

$$T_{11} = T_{21}\left(\frac{P_{11}}{P_{21}}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{for } 0 \leq \Delta P \leq 10 \text{ atmospheres}$$

where

$$T_{21} = 520^{\circ}\text{R for a normal } 60^{\circ}\text{F day.}$$

In regions of greater overpressures it is desirable to compute temperatures on the basis of a normal shock. Values of the peak static temperature, based on a 60°F or 520°R day, have been computed and are presented in Fig. 9.

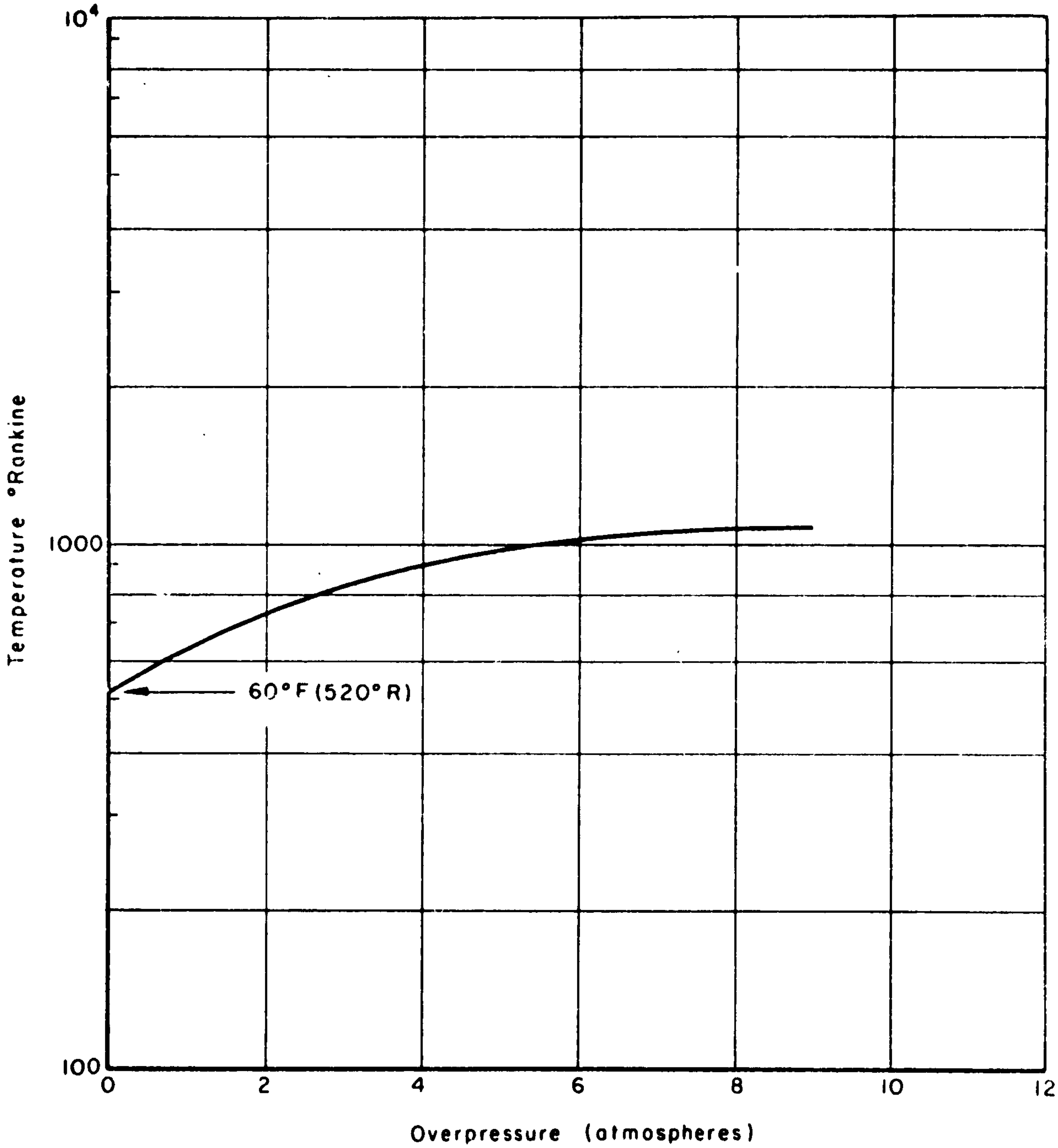


Fig. 9 — Peak shock front static temperature
(Preshock ambient temperature of 520°R, 60°F)

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Part of a broader investigation concerned with the design of shelter structures to withstand the blast or pressure-rise effects of a nuclear explosion. A generalized mathematical model is presented of the rise of pressure with time within an enclosure as a function of enclosed volume, leakage-opening area, static overpressure, and nuclear weapon yield. The results are shown graphically. Their applicability to the design of protected enclosures is illustrated by two examples of personnel shelters: a small home shelter, and a considerably larger arrangement housing up to a hundred people.

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